

Detection of very-high-energy gamma rays from the most distant and gravitationally lensed blazar QSO B0218+357 using the MAGIC telescope system

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QSO B0218+357 is a blazar located at a cosmological redshift of $z=0.944$. It is gravitationally lensed by a spiral galaxy at a redshift of $z=0.68$. The blazar and its lens are well studied in the radio through X-ray bands, and several blazar outbursts were detected by *Fermi*-LAT at energies above 100 MeV. Strong gravitational lensing was invoked to explain the two components apparent in the radio and GeV light curves, separated by 10-12 days. In July 2014 another outburst was observed by *Fermi*-LAT, triggering follow-up observations with the MAGIC telescopes at energies above 100 GeV. The observations were scheduled at the expected time of arrival of the component delayed by the strong gravitational field of the lens, resulting in a firm detection of QSO B0218+357. Using the combined *Fermi*-LAT and MAGIC data sets, we report on variability of this unique blazar, the most distant among all currently known very high energy sources.

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1. Introduction

Even while there are already over 50 blazars¹ detected in the very high energy (VHE $\gtrsim 100\text{GeV}$) range, most of them are relatively close-by sources with redshift $z \lesssim 0.5$. Until recently, the farthest sources observed in this energy range have been: 3C 279 ($z = 0.536$, Albert et al., 2008), KUV 00311-1938 ($z > 0.506$, Becherini et al., 2012) and PKS1424+240 ($z > 0.6$, Acciari et al., 2010). Observations of farther sources in VHE gamma-rays are difficult due to the strong absorption in the interaction with the extragalactic background light (EBL), Gould & Schröder (1966). At the redshift of ~ 1 it results in a cut-off at the energy² of $\sim 100\text{GeV}$. Such energies are at the lower edge of the performance of the current generation of Imaging Atmospheric Cherenkov Telescopes (IACTs), making such observations challenging. To maximize the detection chance, the observations are often triggered by a high state observed in lower energy ranges. In particular, *Fermi*-LAT scanning the whole sky in GeV range can provide alerts of high energy fluxes and spectral shape. Unfortunately due to required integration and processing time and very limited duty cycle of IACTs the inevitable delay of the follow-up observation may exceed the duration of the flare.

QSO B0218+357, also known as S3 0218+35, is a blazar, most probably a flat spectrum radio quasar (FSRQ), located at the redshift of 0.944 (Linford et al., 2012). The object is gravitationally lensed by a galaxy [PBK93] B0218+357 G located at the redshift of 0.68³. The radio image shows two distinct components with the angular separation of only 335 mas and an Einstein's ring (O'Dea et al., 1992). Observations of variability of the two radio components led to a measurement of a delay of 10-12 days (Corbett et al., 1996; Biggs et al., 1999). The delayed component had a 3.57-3.73 times weaker flux (Biggs et al., 1999), however at lower radio frequencies the ratio decreases to ~ 2.6 (Mittal et al., 2006). The difference can be explained to occur due to additional free-free absorption in the line of sight to one of the radio images (Mittal et al., 2007). QSO B0218+357 is one of only two objects with a measured gravitational lensing effect in GeV energy range. In 2012 it went through a series of outbursts registered by the *Fermi*-LAT instrument (Cheung et al., 2014). Even while *Fermi*-LAT does not have the necessary angular resolution to disentangle the two emission components, the statistical analysis of light curve autocorrelation function led to a measurement of time delay of 11.46 ± 0.16 days. Interestingly the magnification factor, contrary to the radio measurements, was estimated to be ~ 1 .

Another flaring state of QSO B0218+357 was observed by *Fermi*-LAT in July 2014 (Buson & Cheung, 2014). The original flare could not be observed by MAGIC due to the full moon period. Observations were scheduled in the expected time of the arrival according to the previously measured by *Fermi*-LAT delay. Those MAGIC observations resulted in the discovery of VHE gamma-ray emission from QSO B0218+357 (Mirzoyan, 2014).

MAGIC (Major Atmospheric Gamma Imaging Cherenkov) is a system of two Cherenkov telescopes located in the Canary Island of La Palma. Due to the large 17m diameter mirror dishes the telescopes perform observations of gamma rays with energies $\gtrsim 50\text{GeV}$. Here we report the results

¹<http://tevcat.uchicago.edu>

²The energy throughout the text is given in the Earth's frame of reference

³<https://www.cfa.harvard.edu/castles/>

of the observations by the MAGIC telescopes which led to the detection of QSO B0218+357 during the flaring state in July 2014.

2. MAGIC: observations and data analysis

In summer 2012 MAGIC finished a major upgrade (Aleksić et al., 2015a) greatly enhancing the performance of the instrument (Aleksić et al., 2015b). The sensitivity of the MAGIC telescopes achieved in the best energy range ($\gtrsim 300$ GeV) is at the level of $\sim 0.6\%$ of Crab Nebula flux in 50 h of observations (for a gamma-ray excess of 5 times the RMS of the residual cosmic-ray background). The angular resolution of MAGIC is of the order of 0.08° , i.e. insufficient for disentangling the emission from the two components of QSO B0218+357.

The telescopes could not follow the original flare seen by *Fermi*-LAT from QSO B0218+357 in 2014 as it appeared during the full moon time, when observations with low energy threshold are not possible. Following the previous measurements of the gravitational lensing delay observations were scheduled in the expected time of arrival of the second component. The observations were performed in 14 nights between 23rd of July and 5th of August 2014 for a total duration of 12.8 h at intermediate zenith angle ($20^\circ - 43^\circ$). The data reduction (stereo reconstruction, gamma/hadron separation and estimation of the energy and arrival direction of primary particle) was performed using the standard analysis chain of MAGIC (Zanin et al., 2013; Aleksić et al., 2015b). As QSO B0218+357 is an extragalactic source, it is affected by $\sim 30\%$ smaller night sky background than the Crab Nebula data used to estimate the telescope performance in Aleksić et al. (2015b). Therefore we were able to apply image cleaning thresholds lower by $\sim 15\%$ with respect to the ones used in the standard analysis presented in Aleksić et al. (2015b), lowering the energy threshold of the analysis. The analysis was performed using a dedicated Monte Carlo (MC) with night sky background and trigger parameters tuned to reproduce as accurately as possible the actual observation conditions.

3. *Fermi*-LAT: observations and data analysis

LAT data collected between MJD 56849–56875 (2014 July 11th – August 8th) were extracted from a circular region of interest (ROI) of 15° radius centered at the QSO B0218+357 radio position, R.A. = $35^\circ.27279$, Decl. = $35^\circ.93715$ (J2000; Patnaik et al., 1992) and analyzed in the energy range 0.3 – 300 GeV using the standard *Fermi Science Tools* (version v9r34p1) in combination with the P7REP_SOURCE_V15 LAT Instrument Response Functions. We applied the gtmktime filter (#3) to the LAT data following the FSSC recommendations⁴. According to this prescription, time intervals when the LAT boresight was rocked with respect to the local zenith by more than 52° (usually for calibration purposes or to point at specific sources) and events with zenith angle $> 100^\circ$ were excluded to limit the contamination from Earth limb photons.

The spectral model of the region included all sources located within the ROI with the spectral shapes and the initial parameters for the modeling set to those reported in the 3FGL (Acero et al., 2015) as well as the isotropic (`iso_source_v05.txt`) and Galactic diffuse (`gll_iem_v05`

⁴http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Likelihood/Exposure.html

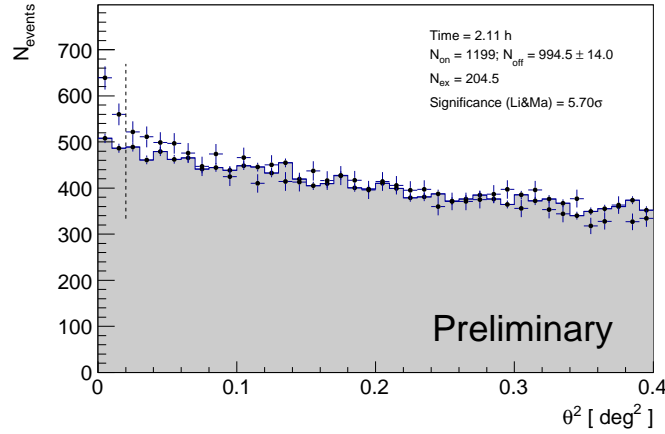


Figure 1: Distribution of the squared angular distance, θ^2 , between the reconstructed source position and the nominal source position (points) or the background estimation position (shaded area). Vertical dashed line shows the value of θ^2 up to which the number of excess events and significance are computed.

. fit) components. In generating the light curve the source of interest was modeled with a power-law spectral shape with normalisation and index free to vary. To access the detection significance we used the Test Statistic (TS) value. The TS quantifies the probability of having a point gamma-ray source at the location specified and corresponds roughly to the square of the standard deviation assuming one degree of freedom (Mattox et al., 1996). It is defined as $TS = -2 \log(L_0/L)$, where L_0 is the maximum likelihood value for a model without an additional source (the 'null hypothesis') and L is the maximum likelihood value for a model with the additional source at the specified location. We note that in our analysis the second model had two more degree of freedom (i.e. normalisation and index were left free), therefore $TS=9$ (25) corresponds to significance of ~ 2.5 (4.6) σ respectively. During the analysed period QSO B0218+357 was not always significantly detected. Flux upper limits at the 95% confidence level were calculated for each interval where the source TS was < 9 .

4. Results

The VHE gamma-ray emission was detected on the nights of 25th and 26th of July, during the expected delayed component of the *Fermi*-LAT flare. The cuts providing the best sensitivity in the 60-100 GeV range according to Aleksić et al., 2015b were used for the source detection. The total observation time during those 2 nights, 2.11 hr, yielded a statistical significance of 5.7σ . (see Fig. 1).

The light curve obtained by MAGIC above 100 GeV is compared with the emission observed above 0.3 GeV by *Fermi*-LAT in Fig. 2. The *Fermi*-LAT emission during the expected delayed component of the flare is a factor 20 higher than the average state of the source (Acero et al., 2015). During both components of the flare the photon index was significantly harder (Buson et al., 2015) than the average one (Acero et al., 2015). A fit with a simple Gaussian function gives the characteristic time scale of the MAGIC flare below 1 day. The two flaring nights give the mean flux

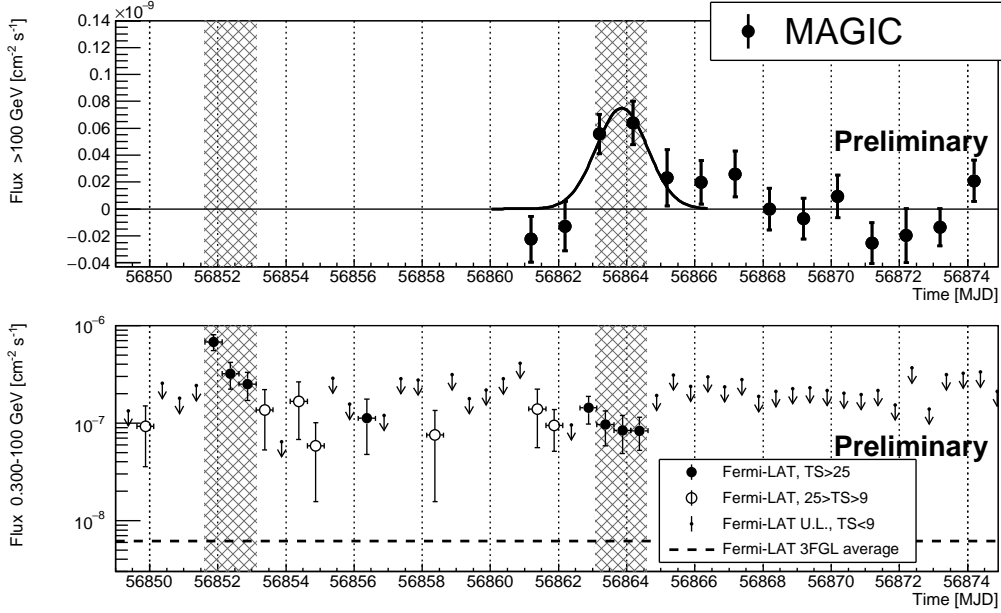


Figure 2: Light curve of QSO B0218+357 during the flaring state in July/August 2014. Top panel: nightly MAGIC fluxes above 100 GeV (points) and a Gaussian fit to the peak position (thick solid line). Bottom: *Fermi*-LAT emission above 0.3 GeV binned in 12 h bins (plotted in log scale). The shaded regions (separated by 11.5 days) show the original and delayed flare following (Buson et al., 2015). Vertical dashed line is the average flux of QSO B0218+357 above 0.3 GeV (Acero et al., 2015)

of $(5.8 \pm 1.6_{\text{stat}} \pm 2.4_{\text{syst}}) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$ above 100 GeV. The relatively large systematic error is a result mainly of a 15% uncertainty in the energy scale.

5. Discussion and conclusions

The MAGIC telescopes has detected VHE gamma-ray emission from gravitationally lensed blazar, QSO B0218+357, during the second component of a flare in July 2014. The previously known delay made it possible to schedule the observations in advance, allowing to see also the raise of the flare. QSO B0218+357 and, detected a few months later, PKS1441+25 (Mirzoyan, 2015; Mukherjee, 2015), are currently the two most distant sources (redshift $z \sim 0.9$) known to emit in VHE gamma-rays. Moreover QSO B0218+357 is the only gravitationally lensed blazar detected at the VHE energies. The spectral features of the emission, modelling and impact on the EBL measurements will be discussed in future work.

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